Large-Eddy Simulations of Baroclinic Instability and Turbulent Mixing

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LONG-TERM GOAL

The long-term goal of this project is to improve our ability to understand, model and predict lateral mixing and the associated submesoscale physical structure and processes in the upper and interior ocean.

OBJECTIVES

The main objective of this project is to examine the interaction between baroclinic, mesoscale eddies and turbulence using a large-eddy simulation (LES) model. Cases will focus on strong, baroclinic waves that form in the mixed layer along surface fronts with scales of a few km, and on mesoscale eddies that are imbedded within larger scale frontal regions. Our goal is to quantify, understand, and ultimately parameterize the physical processes that lead to lateral mixing. Simulations will help guide field experiments planned as part of the Lateral Mixing DRI, and provide a tool for understanding observations in the analysis phase of the project.

APPROACH

High-resolution simulations of baroclinic instability and the interaction of mesoscale flow with turbulent mixing are conducted and analyzed using a large-eddy simulation model. Our analysis centers on quantifying and understanding the mechanisms by which small-scale turbulent structure develops on the mesoscale field, the physical processes and balances that control lateral mixing of fluid properties across the unstable front, and the transition from strongly horizontal, geostrophic motion on the mesoscale to three-dimensional, quasi-isotropic, non-hydrostatic motion on turbulent scales.

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WORK COMPLETED

Research during the first year of this project has focused on selecting an appropriate model domain for examining the interaction of turbulence with baroclinic instability. Initially we chose an open boundary model configuration with a single front centered in the model with periodic along front boundaries and open cross frontal boundaries. This approach was reasonable for simulating unforced cases, however, addition of wind forcing lead to problems with shear in the cross frontal direction. A second model domain based on periodic boundaries in all directions was developed with a double frontal system, similar to the structure of a filament. Results from the double front case are presented here.

RESULTS

Geostrophic Upper-Ocean Front

Frontal simulations were initialized using density gradients outlined in Samelson (1993) and Fox-Kemper et al. (2008), with the cross-frontal density structure set using,

$$b = N^2(z + H_o) + \frac{L_f M_f^2}{2}\tanh\left[\frac{2(y - y_o)}{L_f}\right] + b_o$$

where $b = -g\rho/\rho_o$, $N = \sqrt{\frac{-g}{\rho_o}\frac{\partial\rho}{\partial z}}$, z is the depth, H_o is the mixed layer depth, L_f is the frontal width, M_f is horizontal buoyancy gradient proportional to the Coriolis term f, y is the lateral direction, and b_o is the background buoyancy. Two values for the buoyancy frequency, N, were imposed representing the mixed layer and underlying pycnocline. Parameter selection for this initialization was set according to the theoretically fastest growing baroclinic mode (Stone 1970) with wavelength defined by,

$$L_s = \frac{2\pi U}{|f|}\sqrt{\frac{1+Ri}{5/2}}; \quad \text{where} \quad Ri = \frac{N^2 f^2}{M^4}, \quad U = \frac{M^2 H}{f}.$$

Here we selected a temperature gradient of 0.1-0.2 ^{o}C over a distance of L_f = 600 m, which generated a baroclinic wavelength of about 5-10 km.

Simulations were conducted using a periodic domain with a rigid lid and flat bottom surface. Grid dimensions for the model were set to 1920 points in the cross frontal direction, 2500 points in the along frontal direction and 25 levels in the vertical. With a grid spacing set to 6 m, the resulting domain size was 11.52 km by 15 km horizontally with a depth of 125 m.

Vertical temperature in the model was set to a constant 17 ^{o}C between the surface and 80 m depth, with a constant temperature gradient thermocline of 0.023 ^{o}C/m below 80 m to the model lower boundary. We initialized a double front as shown in Figure 1a with a current structure set by assuming a thermal wind balance.

No Wind Forcing

Frontal instabilities typically required about 3 days before gaining noticeable strength. As shown in Figure 1, after 4 days, the fronts develop cusps suggesting that the baroclinic waves are forming vortices or "occluding" as the circulations evolve. Small scale disturbances form along the strongest frontal zones, for example at y = 4000 m, x = 2000 m. These features are more distinct in plots of the vertical velocity as presented in Figure 1c and the meridional velocity shown in Figure 1d. In general we find that turbulence, or small scale three-dimensional disturbances, are focused along zones of strong horizontal shear and may be a result of horizontal and vertical shear instability.

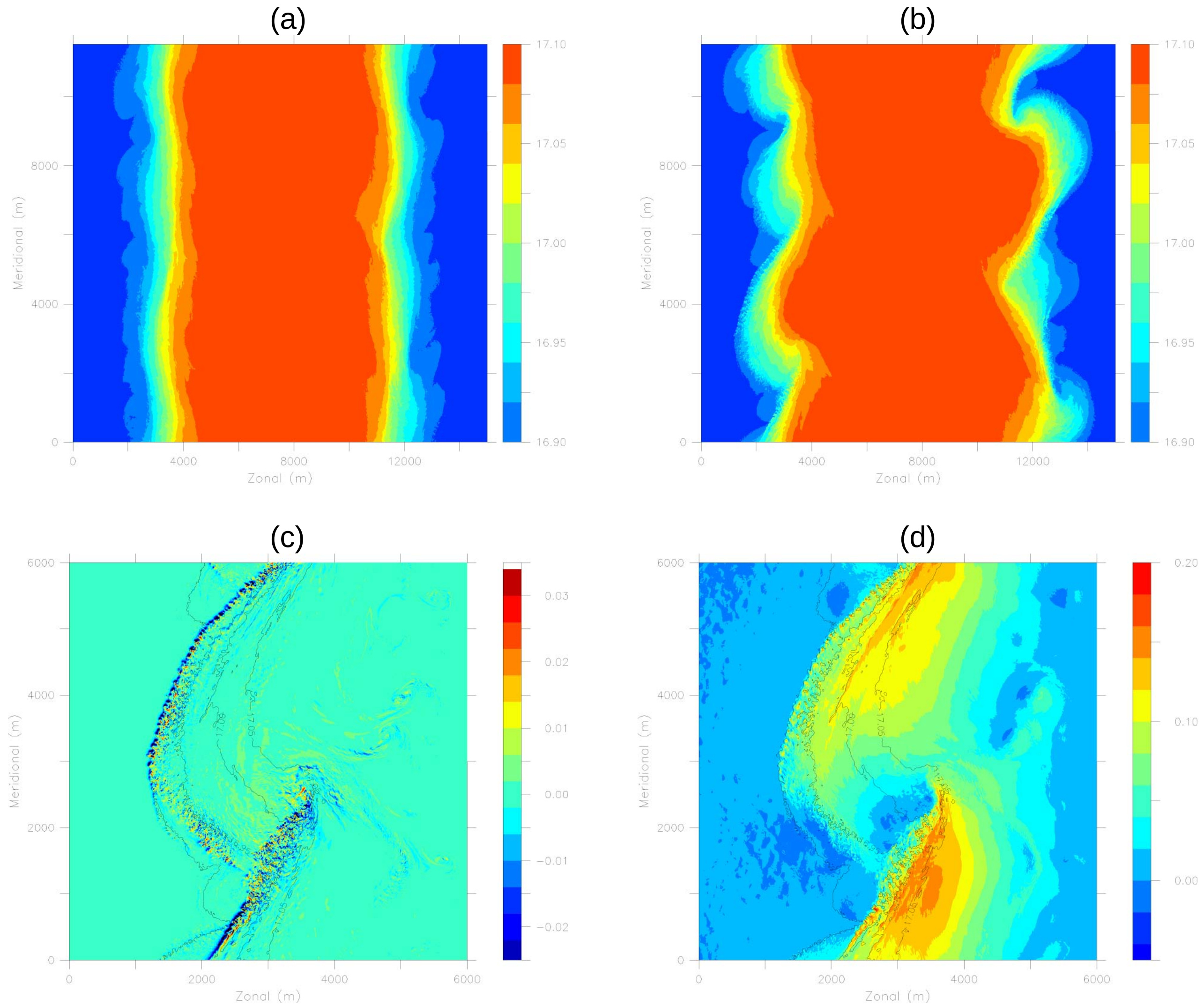

Figure 1. Simulated surface temperature after (a) 3 days and (b) 4 days without wind forcing. The initial temperature gradient in this case was 0.1 °C over ~600 m. Also shown is the (c) vertical velocity and (d) along front velocity for the baroclinic wave in the lower left region of the domain at day 4.

Wind Forcing

It is well known that mixing in the ocean surface layer is dominated by the effects of wind and waves. In particular, Langmuir circulation is thought to play a key role in forcing vertical mixing during wind events. We include the effects of wind and waves by adding an extra term to the momentum equations that accounts accounts for wave-current interaction (see Skyllingstad and Denbo 1995; McWilliams et al. 1997). Our goal in these experiments was to determine if wind and wave forcing disrupts the processes leading to baroclinic instability and develop an understanding of how turbulence dissipation controls lateral mixing.

Simulations were conducted with a wind stress forcing of 0.1 N m^{-2} with a Stokes drift for a monochromatic wave with wavelenth 30 m and height of 1 m. Results from the model for a wind direction in the along-front direction are shown in Figure 2. Wind forcing in this case has a dramatic impact on the formation of eddies for the front on the left side of the domain. Ekman drift in the surface currents toward the east for this front tends to move warm water over cold, stabilizing the water column and changing the baroclinic growth rate. Increased vertical stability also increases the wavelength of maximum growth, however, at this time a dominant wavelength has not been established. Langmuir circulation in combination with Ekman transport also contributes directly to lateral mixing by blending warmer surface waters that have moved over cooler water below the front.

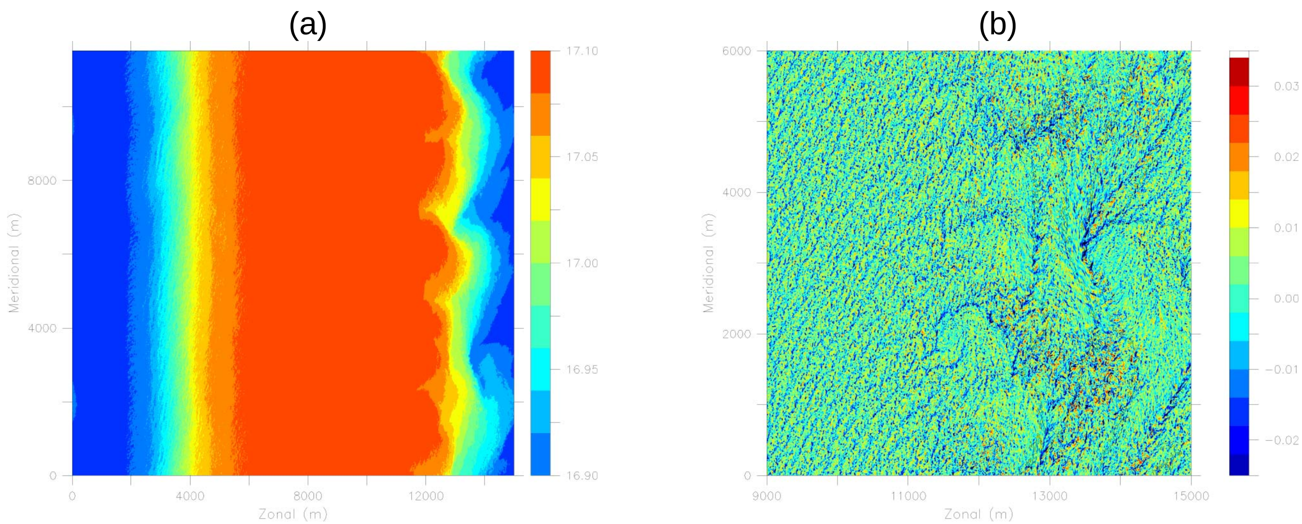

Figure 2. (a) Surface temperature (^oC) and (b) vertical velocity (m s-1) at 6 m depth after 3 days with wind forcing oriented in along the front.

Baroclinic instability is not supressed by the wind for the front on the right side of the domain. In fact, the growth rate has increased as shown by comparing this plot with Figure 1a for the no wind case. Here, Ekman drift is causing advection of cold water over warm, which decreases the vertical stability over time, leading to more rapid waves development.

Wind and wave forced circulations or Langmuir circulations are evident in Figure 2b as shown by the coherent velocity features oriented from right to left when moving southward. Away from the front,

these circulations are relatively continuous with a regular spacing. In contrast, circulations associated with the unstable front tend to dominate over the background Langmuir circulation, again showing strong regions of downward velocity along the more intense temperature fronts. Close inspection suggests that variations in the velocity forced by baroclinic waves both enhance and distort the alignment of Langmuir circulation, especially near the stronger frontal regions.

Future analysis of turbulence processes in conjunction with baroclinic instability will focus on the conversion of baroclinic eddy energy into turbulence kinetic energy and dissipation. One of the major questions we wish to answer concerns the rate at which baroclinic waves dissipate via downscale processes. We are also interested in understanding how wind driven circulations affect this energy exchange and how larger scale effects, such as the Ekman drift, regulate the formation and decay of baroclinic waves.

REFERENCES

Fox-Kemper, B., R. Ferrari, and R. Hallberg, 2008. Parameterization of mixed layer eddies. I: Theory and diagnosis. J. Phys. Oceanogr., 38, 1145-1165.

McWilliams, J. C., P. P. Sullivan, and C.-H. Moeng, 1997. Langmuir turbulence in the ocean. J. Fluid Mech., 334, 1-30.

Samelson, R. M., 1993. Linear Instability of a Mixed-Layer Front, *J. Geophys. Res.*, 98(C6), 10,195–10,204.

Skyllingstad, E.D. and D. W. Denbo, 1995. An ocean large-eddy simulation of Langmuir circulations and convection in the surface mixed layer. J. Geophys. Res., 100, 8501-8522.